Draft CEC PIER-EA Discussion Paper

Greenhouse Gas Inventory Methods

Prepared by:

Amber Kerr – Energy and Resources Group, UC Berkeley

Margaret Torn – Earth Sciences Division, Lawrence Berkeley National Laboratory and Energy and Resources Group, UC Berkeley

For Discussion at the CEC PIER Technical Meetings on the Climate Change Research Plan Update

California Energy Commission

1516 Ninth Street

Sacramento, CA 95814

August 20, 2008

Draft CEC PIER-EA Discussion Paper

Greenhouse Gas Inventory Methods

Disclaimer

The purpose of this paper is to inform discussions among CEC staff, other state agency staff, non-governmental representatives, representatives of academia and other stakeholders regarding the state of the research on greenhouse gas inventory methods in California. In particular, this discussion paper will identify gaps in our understanding and recommendations for future research initiatives with the goal of supporting informed and systematic planning for climate change. This paper is not intended as a research proposal and does not include recommendations regarding specific projects.

1.0 Description of Research Topic

> "When you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."
>
> "If you cannot measure it, you cannot improve it."
>
> ~ Lord Kelvin (William Thomson, 1st Baron Kelvin), 1824 - 1907

Creating accurate and tractable greenhouse gas (GHG) inventories is not an easy task. The Intergovernmental Panel on Climate Change (IPCC) published the first standard inventory guidelines in 1996; since then, researchers worldwide have steadily improved the state of the art. Despite this progress, gaps in knowledge remain – both in fundamental understanding of emissions processes and in application of regionally-specific parameters for better accuracy.

In this paper, we discuss how CEC-PIER could direct its research efforts to improve California's GHG inventory, updating recommendations from an earlier research roadmap (Farrell et al. 2005). We consider all GHGs from all sectors, except for CO_2 emissions from fossil fuel combustion, which is the topic of a separate paper.

1.1 Policy Background

Many states and countries now compile greenhouse gas inventories on a regular basis. The U.S. Environmental Protection Agency (EPA)[1] has done so every year since 1997. California has published its own independent inventory, updated annually since 1999. Both the U.S. and California inventories are based on standard IPCC methodology,[2] with modifications and improvements.

---

[1] Unless otherwise specified, "EPA" is used to refer to the U.S. Environmental Protection Agency rather than the California Environmental Protection Agency.

[2] The IPCC inventory guidelines recently underwent a major update (IPCC 2006).

The California Energy Commission produced California's GHG inventory from 1999 to 2006, until the passage of Assembly Bill 32 (AB 32), the Global Warming Solutions Act. AB 32 mandates that major GHG emitters provide frequent and accurate data on their emissions, beginning April 2009. With implementation of AB 32, the California Air Resources Board (ARB) became responsible for compiling California's greenhouse gas emissions inventory and collecting mandatory reporting data.

AB 32 also mandates that California reduce its emissions to 1990 levels by 2020. This policy goal further increases the importance of California's GHG inventory. In order to develop cost-effective GHG abatement options, it is crucial to have the most accurate estimate possible of the state's emissions—and thus be able to predict how policy changes would affect emissions.

1.2 California's Greenhouse Gas Emissions

California's per capita emissions are relatively low compared to the U.S. average; however, the state's large population makes it a globally significant contributor to climate change. If California were a country, it would be one of the top 20 GHG emitters (Bemis 2006).

California's emissions mix resembles that of the global average: dominated by carbon dioxide (CO_2), with significant contributions from methane (CH_4), nitrous oxide (N_2O), and high global warming potential (GWP) gases. Although CO_2 is largest in magnitude, it is also the best characterized, since its source is predominantly fossil fuel emissions that are relatively easy to estimate. Thus, the non-CO_2 gases contribute roughly as much uncertainty to the inventory as does CO_2. Figure 1 presents California's 2004 emissions by gas species. Since California's inventory currently does not include an uncertainty analysis, we have applied error bars (95% CI) using the percentage uncertainties from the most recent national inventory (US EPA 2008). Note that these error bars only represent a Monte Carlo analysis of parameter uncertainty, and do not address structural uncertainty in the models, which may be considerably greater; this is further discussed in Section 5.5.

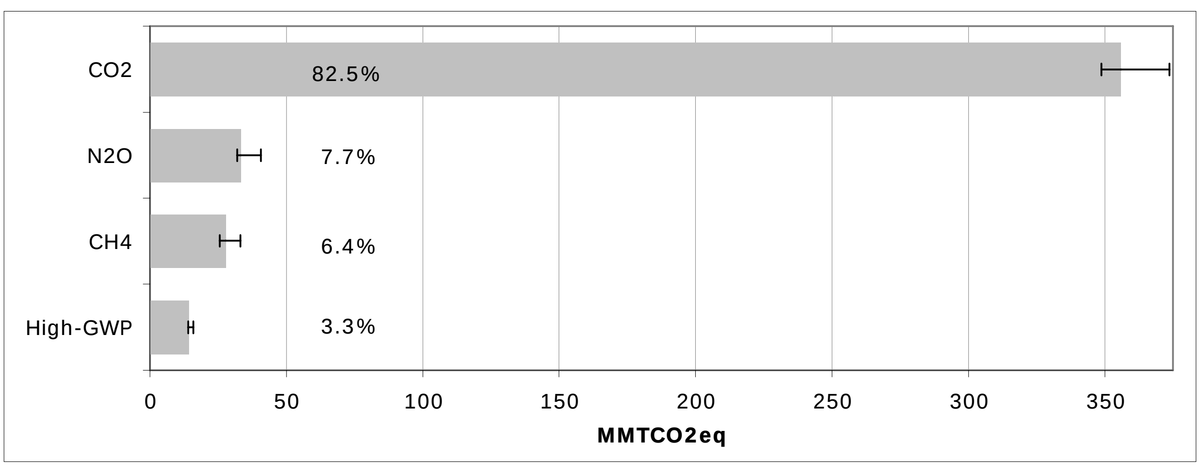

Figure 1: California's 2004 greenhouse gas emissions (Bemis 2006), with uncertainty estimates applied proportionally from the national inventory (US EPA 2008).

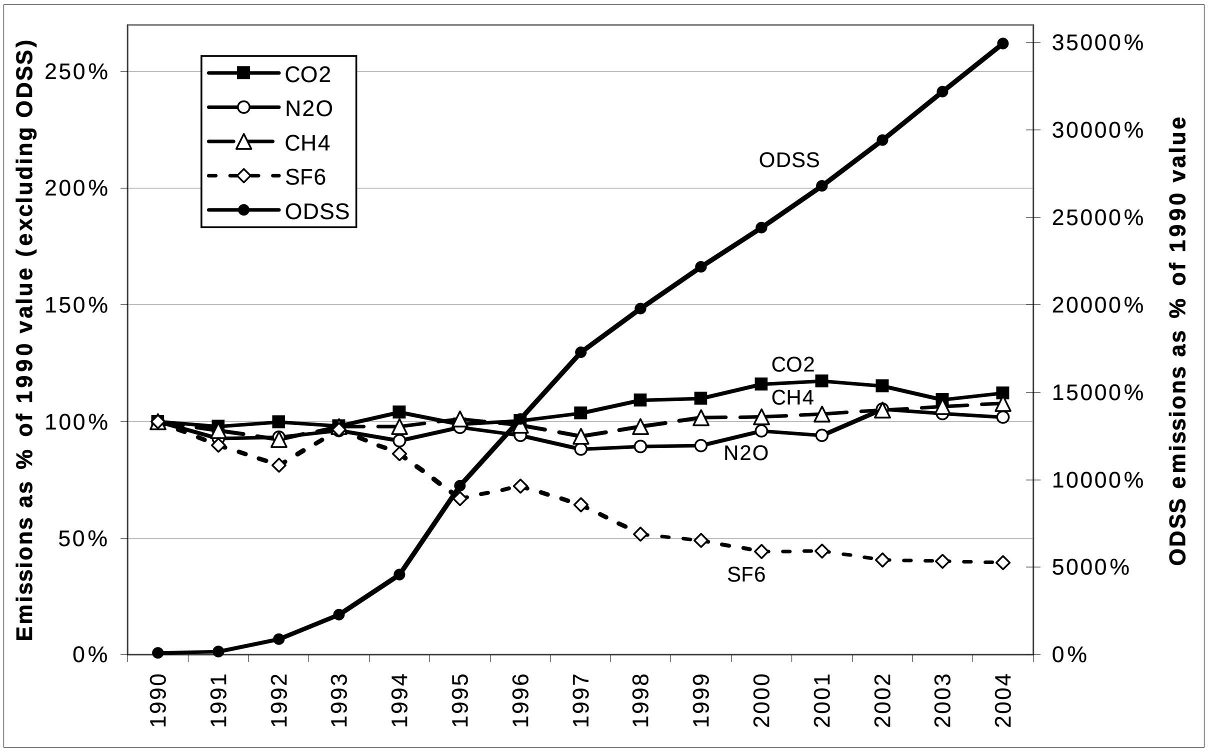

Figure 2: Trends in emissions of greenhouse gas species in California compared to the 1990 baseline (data from Bemis 2006). Ozone-depleting substance substitute (ODSS) emissions (data from CARB 2007) are shown on a secondary Y-axis, due to their near-absence in 1990.

As shown in Figure 2, most GHG emissions in California are not increasing markedly over time, with the exception of ozone-depleting substance substitutes (ODSS)—gases replacing the chlorofluorocarbons and other chemicals banned under the Montreal Protocol. ODSS emissions make up the large majority of high-GWP emissions, currently about 3% of California's total inventory.

1.3 Technical Aspects of Creating a Greenhouse Gas Inventory

It is impossible to directly measure the many diverse sources of greenhouse gas emissions, so GHG inventories rely on a variety of estimation methods. These include:

- Emissions factor[3] multiplied by activity data (may or may not be region-specific);
- Energy balance (how much of each type of energy was used in the state?);
- Simulation model (requires activity data, but is more sophisticated); and
- Inverse modeling (atmospheric measurements to corroborate other approaches).

[3] An emissions factor (EF) is a coefficient that translates activity data (e.g. tons of waste in place at a landfill) into an estimate of GHG emissions (e.g. tons of CO_2 equivalent per year). EFs are often derived as the slope of a regression line through a set of emissions measurements.

IPCC inventory methodology (IPCC 2006) provides guidelines for both emissions factors approaches and simulation model approaches, in cases where the latter are well-developed. The state can choose its preferred method depending on its available data and resources. For more detailed explanations of these methods, see Farrell et al. (2005) and Murtishaw et al. (2005). Inverse modeling is less commonly used, so it warrants a brief explanation here.

Inverse modeling uses measurements of atmospheric concentrations of a given gas species to estimate surface emissions, essentially by transporting the plume backwards to its source. This approach is independent of standard inventory methods. It can be used to estimate emissions of species that have no established bottom-up method[4] (or perhaps do not have known sources), and it integrates over large spatial areas (tens to hundreds of square miles). The goal is to validate the aggregate inventory for each gas species in a region. Inverse modeling may become increasingly important in the coming decades, as changes in industrial and agricultural practices make existing emissions factors less accurate.

We next discuss how these methods can be improved, and the role PIER can play in doing so.

1.4 Goals of this Paper

In an earlier PIER research roadmap on greenhouse gas inventory methods, Farrell et al. (2005) noted four approaches by which California's inventory could be improved:

- Identify and use existing data not yet used in the inventory;
- Perform experiments to collect new data;
- Create new experimental methods to obtain new data; and
- Modify inventory methodology and/or equations.

Any of the latter three activities would constitute research the context of PIER support for research to improve inventory methods. The use of better data sets, by itself, would most likely not.

This framework is compatible with the recommendations of the 2003 PIER Climate Change Research plan (Franco et al. 2003), which proposed the following approach for choosing GHG inventory research projects in California (emphasis added):

- Studying the level of *uncertainties* associated with the different emissions sources;
- Identifying potential *new sources* not being considered in existing inventories; and
- Prioritizing which methods to study in detail with *field studies* and/or *model development* work.

Research efforts should focus on reducing the largest uncertainties. It is worth mentioning that an inventory category of small magnitude may have a disproportionately large contribution to overall uncertainty. Farrell et al. (2005) recommended focusing research not only on inventory categories with the most uncertainty, but on those with the most potential for improvement over the short- or medium-term.

---

[4] In the context of GHG inventories, a "bottom-up" approach uses data from many dispersed individual sources and sums those sources to arrive at an estimate of total emissions (CARB 2008a).

The goal of this paper is to apply these same general principles to identify new specific recommendations for research priorities. In the following sections, we summarize improvements and research that have taken place in the interim, note new needs and gaps that have emerged, and revise the priorities for PIER-funded research.

2.0 Summary of PIER Research to Date on Inventory Methods

Since 2003, PIER-funded research on greenhouse gas inventory methods has focused on four main topics: forest carbon stocks, N_2O emissions from agricultural soils, CH_4 and N_2O from dairies, and monitoring of atmospheric GHG concentrations. Considerable PIER work has also focused on improving estimates of CO_2 emissions from fossil fuels (e.g. Price et al. 2003; Murtishaw et al. 2005); however, as noted above, this discussion paper covers only non-fossil-fuel emissions sources. We briefly review the relevant PIER studies below.

- *Carbon storage in California forests*: Sandra Brown et al. (2004a; 2004b; 2007) of Winrock International developed methods to estimate carbon storage in forests and rangelands in California, consistent with IPCC Tier 3 methods (Paustian et al. 2006). Their work provides the basis for ARB's current inventory methodology in this sector (Tasat and Hunsaker 2008). The same team has also made baseline estimates of forest and rangeland carbon storage for several Western states as part of the WESTCARB effort. A noteworthy result is their estimate of net CO_2 flux from agricultural soils; they conclude that CO_2 emissions from cropland in California are insignificant (40 times smaller) compared to N_2O emissions (Brown et al. 2004).

- *Net greenhouse gas budget of California agricultural soils:* Work by (De Gryze et al. 2006; Six et al. 2006) was funded jointly by PIER and the Kearney Foundation. The authors used the biogeochemical model DAYCENT to estimate the GHG effects of different land management practices in California agriculture, with the goal of identifying and promoting practices that reduce GHG emissions. Although the work focused on climate mitigation, it could readily be applied to inventory improvement.

- *Process modeling of CO_2 and N_2O emissions from agricultural soils in California:* (Li et al. 2004) applied the biogeochemical model DNDC to California on a county-by-county basis to estimate the net GHG contribution of agricultural soils, and also to evaluate the effects of different management options. They concluded that the model was accurate enough to provide useful information on emissions trends, and that most of California's agricultural soils are probably a net GHG sink. However, they emphasized the need for better data and more rigorous model validation.

- *Process modeling of GHG emissions from California dairies*: Salas et al. (2008) empirically measured CH_4 and N_2O emissions from the rumens of dairy cows (enteric fermentation) and from dairy corrals (manure management). They used these data to modify the DNDC model to simulate dairy emissions. Finally, they created a spatial database describing dairy operations in California and simulated statewide emissions. They concluded that the DNDC model showed promise for this purpose, and that its differences from the existing inventory estimates might be instructive.

- *Atmospheric CO_2 monitoring in California*: (Fischer et al. 2005) presented a detailed plan for monitoring and modeling atmospheric CO_2 fluxes from terrestrial ecosystems and fossil fuel use in California, with the goal of better constraining California's carbon budget. This work laid the foundation for the atmospheric measurements of GHGs that are currently underway in California (see Section 3 below).

In summary, PIER-funded research since 2003 has made progress toward closing the gaps in inventory methods; however, there is still room for improvement. Some of these gaps are already being addressed by ongoing or pending research projects, as described below.

3.0 PIER Research Currently Underway

PIER is currently (FY 2008-2009) funding the following three topics relevant to improvement of GHG inventories:

- *Atmospheric measurement of GHGs*: The new California Greenhouse Gas Emissions Measurement (CALGEM) project, led by Marc Fischer of Lawrence Berkeley National Laboratory (LBNL) in collaboration with the National Oceanic and Atmospheric Administration (NOAA), measures ambient GHG concentrations from communications towers in San Francisco and the Sacramento Delta. These empirical concentrations are compared with the predictions of a model that simulates atmospheric transport of the emissions reported in the current inventory. This work will be used to quantify the accuracy with which atmospheric methods can be used to test emissions inventories at local to regional scales. It is expected to guide the development of a state-wide atmospheric monitoring network for California.

  Co-located with the above project, a new sensor is being tested by Diane Saber of Gas Technology Institute (GTI) to monitor the isotopic composition of atmospheric CO_2 and CH_4 in real-time. These highly resolved isotopic data will help to identify the sources of the measured ambient GHGs, enabling a more detailed test of bottom-up inventory methods.

- *N_2O emissions from agricultural soils*: In early 2008, CEC issued a request for proposals on this topic and will be selecting a proposal to fund in August 2008. The new project will produce continuous measurements of N_2O fluxes, using a laser absorption spectrometer operated as an eddy covariance system over agricultural fields. These measurements will be used to test a process-based model of N_2O emissions as a function of fertilizer application, crop and crop management, soil conditions, and climate.

- *CH_4 emissions from landfills*: Jean Bogner, of Landfills, Inc., is heading a three-year project to improve California's inventory methods for landfill methane. The project's goals are: (1) creation of a template for landfill data collection; (2) process-based modeling; and (3) field validation of models (at sites in Monterey and Los Angeles).

4.0 Non-PIER Accomplishments and Opportunities for Collaboration

Many parties contribute to inventory-related research: state and national government bodies, multilateral organizations, universities, consulting firms, and others. In this paper, we do not attempt to summarize the full breadth of recent research; rather, we focus on two organizations whose work is directly relevant to CEC's efforts. These are the US Environmental Protection Agency and the California Air Resources Board.

4.1 U.S. Environmental Protection Agency

The EPA is in charge of the national GHG emissions inventory, which uses methods based on the IPCC guidelines. EPA is actively involved in the revision of inventory methods, sometimes influencing the IPCC guidelines rather than vice versa (Hockstad 2008, pers. comm.). Following are some of EPA's recent inventory modifications, including model development, data collection, and new application of existing data:

- *Agricultural soils:* modified soil nitrogen inputs to be consistent with soil carbon inventory; implemented finer spatial resolution; revised emissions factors (US EPA 2007). Changed manure input assumptions; changed DAYCENT values for sorghum; used state-level data for nitrogen application instead of larger-scale regional data. These changes reduced N_2O emissions estimates for this sector by 27% (US EPA 2008).
- *Land use, land use change, and forestry (LULUCF)*: incorporated more accurate and finer-scale data on land use (US EPA 2007). Used new forest inventory data and refined models for decay of wood products in landfills (US EPA 2008).
- *Enteric fermentation*: included new default values from IPCC's 2006 revisions; updated the Cattle Enteric Fermentation Model to include more detailed input data and state-level outputs; used better population data for horses and swine (US EPA 2008).
- *Manure management:* used climate-specific CH_4 conversion factors for dry manure systems; used better cattle population data; used updated IPCC emissions factors (US EPA 2007). Refined calculations to specify animal group, type of manure management system, and state; included direct emissions from volatilized ammonia; used new emissions factors specific to the type of manure management system, not just to the state. These and other changes increased the estimate of total GHG emissions from this sector by 43% (US EPA 2008).
- *Landfills:* changed the first-order decay model to include a delay time of 6 months; changed the model for industrial landfills (as opposed to municipal landfills) (US EPA 2007). Used better historical data on disposal patterns and more complete data on methane flaring (US EPA 2008).
- *Wastewater*: differentiated between four different systems (septic, central aerobic, central anaerobic, and anaerobic digester); adjusted the per-capita Biological Oxygen Demand (BOD) rate (US EPA 2007).

EPA has research projects currently underway in several areas of the inventory, which may lead to new emissions factors, better input data sets, or new inventory approaches. These activities and their potential benefits should be taken into account when prioritizing research for California's inventory. These activities include (Hockstad 2008):

- Continual refinement of DAYCENT,[5] for example, testing the effect of crop rotation on soil N_2O emissions.
- Reconciliation of land use classification areas. This involves integrating datasets for agricultural carbon with that for forestry to obtain nationally consistent, higher

[5] DAYCENT is a biogeochemical process model used to predict emissions from soils.

resolution estimates of carbon emissions due to land use and land use change. This is being done in collaboration with the US Forest Service and the US Department of Agriculture (See also section 5.4).

- Improving EPA's "Vintaging Model" used to estimate emissions of ozone-depleting substance substitutes by obtaining better data on sales and retirement of products, and equipment leakage rates.
- Empirical estimates of CH_4 emissions from oil and natural gas production, to test and improve inventory methods for fugitive CH_4 emissions.

4.2 California Air Resources Board

As noted above, ARB is in charge of collecting AB 32 "mandatory reporting" data and annually compiling California's greenhouse gas inventory. ARB's Research Division is responsible for many past and current projects on GHG inventory improvement, such as:

- *Atmospheric measurement of CH_4.* There are two types of research underway at ARB using atmospheric CH_4 measurements to improve CH_4 inventories. The first approach is measurement of ambient CH_4 concentrations in well-mixed locations (e.g., the peak of Mount Wilson near Los Angeles) as a tool for cross-checking aggregated CH_4 inventory estimates (Hsu et al. 2007). The second approach is measurement of CH_4 downwind of point sources (e.g., landfills, highways, oil wells, and dairy farms) using a sensor mounted on a mobile platform (Hsu 2008, pers. comm.); this may help to improve default emissions factors.
- *High-GWP gases*. ARB is currently investigating previously unknown HCFC-22 emission sources (Hsu 2008, pers. comm.) and other unknown sources of high-GWP gases.
- *Carbon storage in forests*. The ARB is working with the Climate Change Action Registry, and with relevant stakeholders, to develop accounting protocols for carbon in California forests. This process has not yet resulted in inventory revision; ARB's most recent inventory still used the methodology developed by Brown et al. (2004).
- *N_2O from agricultural soils*. ARB has recently begun funding research on N_2O emissions from agricultural soils; this research is still in the project selection stage. The initial goal of the research is to measure baseline N_2O emissions from nitrogen fertilizer application under California-specific conditions (Guo 2008, pers. comm.).

5.0 Gaps in Research and Knowledge Relevant to California

The research activities described above have greatly improved the completeness and accuracy of California's inventory since it began in 1999. However, there are still notable shortcomings in several sectors of the inventory, as discussed in the following sections.

5.1 N_2O Emissions from Agricultural Soils

In 2005, Farrell et al. recommended that estimates of N_2O emissions from agricultural fertilizer applications should be PIER's top research priority for GHG inventory improvements. Specifically, they recommended funding research to produce data that could be used to test both process-based and emissions factor models. The latter are the basis of the current California inventory, but EPA uses a process model (DAYCENT) for agricultural N_2O emissions. Process models can potentially be more accurate than emissions factor models, providing that data are sufficient and the system is well-understood. However, that is not necessarily always the case with agricultural N_2O emissions (Riley 2008, pers. comm.).

We believe that the following research is still needed:

- A model intercomparison, in which the predictions of various process-based models and the current emissions factor model are compared to data. DAYCENT and DNDC were being compared at the time of the 2005 research roadmap (Farrell et al. 2005) but improvements have been and other models should be considered, so further testing would be useful;
- Collecting and using more empirical data (CARB 2008c) to improve an emissions factor model or process-based model for the state inventory;
- Calculation of uncertainty in N_2O emissions inventories generated at the state and national level (and presumably based on lower resolution datasets); and
- Better characterization of indirect N_2O emissions, a related topic described below.

5.2 Indirect N_2O Emissions

Indirect emissions occur when nitrogen-containing compounds leave agricultural soil, through leaching or volatilization, where the nitrogen input took place, and then emit N_2O from a different location. Indirect N_2O emissions can be substantial, in some cases equaling or exceeding direct N_2O emissions (e.g. Mosier et al. 1998). Estimates of indirect emissions are very uncertain; the uncertainty is typically assumed to be about 100% of the direct inventory.

The IPCC default emissions factor (EF) for direct N_2O emissions from agricultural soils, based on field studies, is 1% (with a range of 0.3% to 3%) of nitrogen fertilizer applied. For indirect emissions, IPCC's default effective EF is 0.3% to 0.45% (with a range of 0.3% - 3%). However, a recent study of measured atmospheric concentrations of N_2O concluded that the global average emissions factor for direct plus indirect emissions must be between 3% and 5% (Crutzen et al. 2008). While the latter EF may be larger than that of the IPCC, and the discrepancy between approaches is the subject of scientific debate, both approaches concur that indirect emissions are significant.

Most inventories, including California's, estimate indirect emissions using default IPCC emissions factors. The current ARB inventory assumes that 1% of volatilized nitrogen becomes N_2O, and 0.75% of leached nitrogen becomes N_2O (Tasat and Hunsaker 2008). This crude approach could potentially be improved upon by process modeling. EPA has already implemented a process model, DAYCENT, to predict both direct and indirect N_2O emissions. However, DAYCENT indirect emissions predictions have not been tested (nor have they for the emissions factor approach, since collecting such data is difficult).

For California, it would be valuable to evaluate the new literature on this topic, as a first step. In the medium-term, it would be valuable to conduct a study to test predictions of indirect emissions by biogeochemical process models (and other methods). Predictions could be tested using new, detailed reactive chemical transport models (e.g., ToughReact) and by conducting experiments that allow empirical measurement of indirect emissions.

5.3 High-GWP Gases

California produces a disproportionate share of high-GWP gases. As of 2004, they accounted for 3.3% of California's inventory, compared to 2.0% of the national inventory (US EPA 2008). Currently, the inventory estimates are based on default IPCC or EPA methodology, in some cases simply multiplying a national per-capita emissions factor by California's population (CARB 2008b). However, the sources of these gases are not completely characterized, and their emissions are growing rapidly (see Figure 2), so this should be a high priority for research. For example, it would be helpful to gather California-specific data on SF_6 emissions from electric utilities (Bemis 2006; Tasat 2008).

5.4 Missing Species and Sources

California's current inventory completely omits some gas species and sources that could potentially be quite important. Some notable omissions include:

Ozone precursors

Tropospheric ozone (O_3) is the third-most important GHG, but it is not included in GHG emissions inventories because it is a secondary pollutant and because it is not well-mixed in the atmosphere, having a lifetime in the troposphere on the order of weeks. Ozone is formed from two precursors, organic gases (volatile organic compounds, VOCs) and nitrogen oxides (NO_X), in sunlight. In accordance with the IPCC guidelines, the U.S. inventory reports emissions of NO_X and non-methane VOCs; methane is included in the inventory separately (US EPA 2004). Similarly, ARB has been reporting emissions of ozone precursors for many decades. At both national and state levels, non-methane precursor emissions are listed in mass of each gas, not CO_2 equivalent, because there are no agreed-upon methods for estimating the GWP of ozone or its precursors (Farrell et al. 2005).

The radiative forcing effect of tropospheric ozone and its precursors is a significant gap in GHG inventories, at the state, national, and global levels. As a world leader in modeling ozone formation and predicting ozone concentrations, the California Air Resources Board may be in a special position to help address that gap. Although ARB (and EPA) are not required to include the global warming contribution of ozone or its precursors in their GHG inventory, ozone will eventually have to be controlled to mitigate climate change. This may be a pathbreaking opportunity for the state, with potential synergies between ARB capabilities and CEC funding.

The research needs for this topic identified by Farrell et al. (2005) still apply, namely:

- Evaluate potential approaches to inventorying ozone or ozone precursors in metrics of radiative forcing or GWP for the California GHG inventory, in coordination with national and international efforts; and
- Investigate the development of methods for relating emissions to global background concentrations of ozone in coordination with air quality agencies and IPCC.

CO_2 from agricultural soils

Currently, the California GHG inventory does not include CO_2 emissions from agricultural soils, although the national inventory does. Agricultural management can cause large CO_2 emissions from soils, for example from tillage or fallow periods. Conversely, increased plant productivity, e.g., due to irrigation or fertilization, may lead to soil carbon sequestration.

There are two promising approaches for adding this source to the emissions inventory: soil carbon inventories and process-based models. EPA employs the former approach, estimating annual soil CO_2 fluxes based on the change in soil carbon stock over time documented in the United States Department of Agriculture (USDA) Natural Resources Conservation Service National Resources Inventory (NRI). Stephen Ogle et al. (Ogle 2008, pers. comm.) have developed a process model for CO_2 emission inventories, based on DAYCENT and validated with NRI data. This model could be further validated and tested in California, informed by the existing California-focused DAYCENT work of Six et al. (2006).

Although there has been much research on agricultural CO_2 fluxes, it could be valuable to conduct research in California because: (a) methods for predicting land use emissions tend to be location-specific, and need to be parameterized and tested locally; and (b) California has fairly atypical ecosystems. We suggest that research on agricultural CO_2 emissions for California's inventory focus on predicting emissions from Delta soils (Tasat and Hunsaker 2008) and from newly cultivated areas, since these are likely to be the largest sources. The US Geological Survey has a project measuring Delta GHG emissions, in collaboration with UC Berkeley, which may be leveraged for this effort.

Combining agricultural and forestry sectors

EPA recently adopted the IPCC 2006 methodology for emissions from land use, which groups the agricultural and forestry sectors together. To do so, EPA relies on national databases of carbon stocks (Hockstad 2008), estimating CO_2 emissions from land use change as the difference in ecosystem carbon stocks between observation periods. EPA is using data products from the US Forest Service Forest Inventory Assessment (FIA) and USDA-Natural Resources Conservation Service (NRCS) National Resources Inventory (NRI). These and other relevant data sets are being aligned in EPA's Land Area Reconciliation Project. California is not currently utilizing these datasets, as far as we know, but they contain high quality data that is not duplicated by other datasets available in California. This is a resource that could be leveraged in developing or improving inventory methods. A recent meta-analysis (Ito et al. 2008) suggests significant discrepancies between different methods of estimating carbon fluxes from land-use change and forestry; cross-checking and combining existing data sets could help to reduce this discrepancy.

Aerosols

Primary and secondary aerosols, such as sulphate particles and soot, are not included in GHG inventories for several reasons: they are short-lived and, thus, not well mixed in the atmosphere; many aerosols are secondary pollutants; and the radiative forcing from different aerosols is highly uncertain and locally variable. Enabling the inventory of aerosol species would facilitate their control and would make a valuable contribution to climate change science. However, the large, interdisciplinary, long-term research effort required to make progress is probably beyond the scope of CEC-PIER at this time.

Other missing sources

We feel that the sources listed above are the most significant omissions from California's GHG inventory. However, the list of other missing sources is long, and includes N_2O emissions from septic tanks; net balance of food imports and exports; and use of nitrogen fertilizers in urban areas (Tasat 2008).

Prioritizing these missing species and missing sources should be done on the basis of their potential magnitude and their tractability, and to a lesser extent, based on their potential for change in the next 10-40 years. Species for which we have no tools for creating an inventory may need large, basic research programs before they are ripe for support by an agency that expects an improvement from a few years of modest levels of funding.

5.5 Uncertainty Analysis

There has not yet been a systematic analysis of uncertainty in California's greenhouse gas inventory. Such an analysis could provide more targeted information on which sectors and methods are most in need of improvement, and allow a more rigorous assessment of changes in emissions over time. For the past several years, the national inventory has included Monte Carlo estimates of parameter uncertainty (US EPA 2008, Annex 7); these estimates describe uncertainty in the input data and parameters. A similar analysis could be applied to California's inventory with relative ease.

More difficult, but potentially more valuable, would be an attempt to address structural model uncertainties, such as a missing process in a model. Inaccuracies caused by structural flaws in a model can overwhelm inaccuracies caused by imperfect data. Recent revisions to the models used in the EPA inventories (US EPA, 2007; 2008) have changed inventory estimates far in excess of their Monte Carlo uncertainty; for example, 2008 changes to manure management calculations revised that sector's GHG estimates downward by 47%.

Model uncertainty can be evaluated through comparison with empirical data sets. For example, Ogle et al. (2007) compared CENTURY's soil carbon predictions with data from several field studies, thus identifying conditions under which the model tended to under- or overestimate soil carbon. Similar studies using California-specific data could be very instructive for almost any category of the inventory. Research to identify processes or pathways that warrant increased emphasis in an inventory method is also important for addressing these kinds of model weaknesses.

6.0 Conclusions and Prioritized Recommendations

6.1 Conclusions

The state-of-the-art for California's greenhouse gas inventory has undergone many revisions since the inventory began in 1999, but there are still major shortcomings to be addressed. These improvements can benefit not only California, but also other states and countries.

California is currently in a unique position to advance GHG inventory methodology for at least three reasons:

- With passage of AB 32, mandatory reporting of emissions will enable unprecedented accuracy and wealth of data;
- California is a large state, and so its emissions are significant on a global scale; and
- California has distinct economic specializations (high-tech and agriculture, for example), so it is well-poised to contribute to research in those sectors.

In deciding how to focus its research funding, PIER must be careful not to duplicate or conflict with efforts already underway by ARB and EPA (as described above). Working closely together is of paramount importance. In the final section below, we recommend areas in which PIER could most effectively focus its research support.

6.2 Prioritized Recommendations

The priorities below reflect our understanding of the magnitude of the emissions category, its uncertainty, and the potential for improvement through California-funded research. In addition, we took into consideration PIER's funding criteria: (1) relevance to PIER objectives; (2) likelihood of generating results within five years; (3) applicability to California policy-making related to climate change; (4) potential to advance scientific understanding; (5) potential to generate co-benefits in science or policy in other areas; (6) likelihood of securing co-funding from other agencies; and (7) a clear need for state support.

Some of the inventory modifications described above (e.g., integration of agricultural and forestry data sets) involve work to make use of better data sets. There are many cases in which newly available data will enable a new inventory method, or a revision in methods will create demand for different data sets. However, given a technically-sound inventory method, utilization of existing data does not in itself constitute a PIER research project, and the need (or opportunity) to identify and use new data was not a ranking criterion in our recommendations.

Table 1 lists our recommendations, comparing our 2008 ranking with the ranking suggested in 2004 (Farrell et al. 2005), and noting the reasoning behind any change in priority.

Table 1: Prioritized recommendations for PIER-funded greenhouse gas inventory research

GHG Emissions Category	Priority		Rationale for change in priority
	2008	2004	
High Priority			
CO_2 from agricultural soil; reconciliation with forestry methods	1	n/a	Data and potential methods improved
N_2O from agricultural soils (including indirect emissions)	2	1	Better potential to implement process model approach
High-GWP gases	3	3	Understudied, rapidly increasing
Fugitive CH_4 emissions	4	n/a	Understudied relative to other categories of similar magnitude
CH_4 from landfills	5	2	Large category needing CA data, but PIER research underway
Medium Priority			
Ozone (precursor inventory)	6	5	Not required in inventory
Inverse Methods	7	7	PIER research underway
Low Priority			
N_2O from mobile sources	8	9	Now uses IPCC 2006 emissions factors in ARB model
CH_4 from enteric fermentation	9	4	PIER study recently completed
CH_4 and N_2O from manure management	10	6	PIER study recently completed
CH_4 and N_2O from wastewater	11	8	EPA methods sufficient

We hope that these conclusions follow naturally from the body of this paper; however, we wish to make several additional points for clarification.

CO_2 from agricultural soils has not changed in importance since 2004; however, that topic was not in the scope of our report at the time, nor were the methods and data sets as well developed. We believe that this is an important category that could be included in the California inventory with relative ease, given the extensive work already completed.

N_2O from agricultural soils has been better characterized since 2004, but there are still improvements to be made. The ongoing efforts of CEC-PIER and ARB are commendable and should certainly be continued. At this point, California faces a decision about whether to continue with the emissions factor approach or to implement a process model; future research should focus on resolving this question. An advantage of a process model is its applicability to indirect N_2O emissions, one of the largest sources of uncertainty in the inventory overall.

CH_4 from landfills has also been better addressed since 2004, and we hope that the current work of Bogner et al. will lead to major improvements. Since this sector is so large in magnitude, we recommend keeping it on the list of research priorities for the time being.

High-GWP gases should garner ongoing research funding due to their alarmingly rapid atmospheric increase. Another category of the same magnitude, though with much less rapid increase, is fugitive CH_4 emissions from oil and gas production. These fugitive emissions have not yet received intensive study, and better empirical measurements could significantly improve the accuracy of their inventory estimates in California.

Inverse modeling, although not a standard inventory method, is a valuable tool for testing the accuracy of all other inventory methods. EPA is not doing research on inverse methods, implying a greater role for state-funded research. ARB's expertise in atmospheric measurements could lead to fruitful collaborations with PIER on this topic.

California's state agencies have a remarkable history of public-interest research, which is more needed than ever in tackling the challenge of climate change. We applaud the progress that has been made on GHG inventory methods in recent years by CEC-PIER and other agencies, and we hope that our suggestions will provide a helpful guide to future efforts.

7.0 Acknowledgments

We are indebted to Gerry Bemis of the California Energy Commission for discussions and for writing text for an earlier draft. Leif Hockstad, of the U.S. Environmental Protection Agency, briefed us on national inventory research. Webster Tasat and Larry Hunsaker, of the California Air Resources Board, generously provided information on ARB's inventory work. Ying-Kuang Hsu, also of ARB, shared his team's work in progress on atmospheric measurements of CH_4 and high-GWP gases. Marc Fischer of LBNL discussed his inverse modeling work with us. We are also grateful to Bill Parton and Stephen Ogle, of Colorado State University, for their thoughts on biogeochemical modeling of N_2O emissions.

8.0 References

Bemis, G. (2006). "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004." Sacramento, CA: California Energy Commission. CEC-600-2006-013-SF. 117 pp.

Brown, S.; T. Pearson; A. Dushku; J. Kadyzewski and Y. Qi (2004). "Baseline Greenhouse Gas Emissions for Forest, Range, and Agricultural Lands in California." Sacramento, CA: Winrock International, for the California Energy Commission. 500-04-069F. 80 pp.

CARB. (2007). “Draft California Greenhouse Gas Inventory (millions of metric tonnes of CO2 equivalent) - By IPCC Category.” Retrieved 19 November 2007, from http://www.arb.ca.gov/cc/inventory/data/data.htm.

CARB (2008a). “Climate Change Draft Scoping Plan: Appendices.” Sacramento, CA: CA Air Resources Board. June 2008 Discussion Draft. 264 pp.

CARB. (2008b). “Documentation of California's Greenhouse Gas Inventory.” Retrieved 7 August 2008, from http://www.arb.ca.gov/cc/inventory/doc/doc_index.php.

CARB. (2008c). “Research on N2O Emissions from Agricultural Soils in California.” Retrieved 21 May 2008, from http://www.arb.ca.gov/ag/fertilizer/presentations/n2o_5_19_08.pdf.

Crutzen, P. J.; A. R. Mosier; K. A. Smith and W. Winiwarter (2008). “N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels.” *Atmospheric Chemistry and Physics* 8: 389-395.

De Gryze, S.; J. Six; S. Wicks; R. Catala-Luque and R. Howitt (2006 of Conference). “Calculating the Agricultural Greenhouse Gas Budget at the County Level in California.” 18th World Congress of Soil Science, Philadelphia, Pennsylvania, 15 July 2006.

Farrell, A. E.; A. R. Brandt; A. C. Kerr; M. S. Torn and G. Franco (2005). “Research Roadmap for Greenhouse Gas Inventory Methods.” Sacramento, CA: California Energy Commission. CEC-500-2005-097. 131 pp.

Fischer, M. L.; W. J. Riley and S. Tonse (2005). “Development of an Implementation Plan for Atmospheric Carbon Monitoring in California ” Sacramento, CA: California Energy Commission. CEC-500-2005-123. 43 pp.

Franco, G.; R. Wilkinson; A. H. Sanstad; M. Wilson and E. Vine (2003). “Climate Change Research, Development, and Demonstration Plan.” Sacramento, CA: California Energy Commission. P500-03-025FS. 66 pp.

Guo, L. (CA Air Resources Board). Personal communication to A. C. Kerr. 8 August 2008.

Hockstad, L. (US EPA). Personal communication to M. S. Torn and A. C. Kerr. 7 August 2008.

Hsu, Y.; C. Jakober; R. VanCuren; M. FitzGibbon; S. Rider; M. McDougall; A. Baker; K. Gorham, et al. (2007 of Conference). “Recent Greenhouse Gas Monitoring for Methane Inventory Reconciliation in Southern California.” 4th Annual Climate Change Research Conference, Sacramento, CA, September 10, 2007.

Hsu, Y.-K. (CA Air Resources Board). Personal communication to G. Bemis. 18 July 2008.

Author (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe. Hayama, Japan: Institute for Global Environmental Strategies (IGES), on behalf of the IPCC. Available online at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Ito, A.; J. E. Penner; M. J. Prather; C. P. de Campos; R. A. Houghton; T. Kato; A. K. Jain; X. Yang, et al. (2008). "Can we reconcile differences in estimates of carbon fluxes from land-use change and forestry for the 1990s?" *Atmospheric Chemistry and Physics,* 8: 3291-3310.

Li, C.; W. Salas and M. Los Huertos (2004). "Quantifying Carbon Dynamics and Greenhouse Gas Emissions in Agricultural Soils of California: A Scoping Study." Sacramento, CA: California Energy Commission. 500-04-038. 62 pp.

Mosier, A.; C. Kroeze; C. Nevison; O. Oenema; S. Seitzinger and O. van Cleemput (1998). "Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle." *Nutrient Cycling in Agroecosystems* 52(2-3): 225-248.

Murtishaw, S.; L. Price; S. de la Rue du Can; E. Masanet; E. Worrell and J. Sathaye (2005). "Development of Energy Balances for the State of California." Sacramento, CA: California Energy Commission. CEC-500-2005-068. 72 pp.

Ogle, S. (National Resource Ecology Laboratory, Colorado State University). Personal communication to M. S. Torn. 10 August 2008.

Ogle, S. M.; F. J. Breidt; M. Easter; S. Williams and K. Paustian (2007). "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205: 453-463.

Paustian, K.; N. H. Ravindranath and A. van Amstel (2006). "Agriculture, Forestry, and Other Land Use." Vol. 4 in. City: Institute for Global Environmental Strategies (IGES), on behalf of the IPCC.

Price, L.; J. Sathaye; C. Mamay; E. Worrell; S. Murtishaw; D. Fisher and A. Phadke (2003). "Research in Support of California's Greenhouse Gas Emission Reduction Registry." Sacramento, CA: California Energy Program. 500-04-008. 49 pp.

Riley, W. J. (Lawrence Berkeley National Laboratory). Personal communication to A. C. Kerr. 1 August 2008.

Six, J.; S. De Gryze; R. Howitt; R. Catala and S. Wicks (2006 of Conference). "Regional Projections of Net GHG Emissions and Reductions in California Agriculture." 3rd Annual Climate Change Research Conference, Sacramento, CA, 13 September 2006.

Tasat, W. (CA Air Resources Board). Personal communication to G. Bemis. 10 June 2008 and 26 June 2008.

Tasat, W. and L. Hunsaker (CA Air Resources Board). Personal communication to M. S. Torn and A. C. Kerr. 1 August 2008.

US EPA (2004). "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2002." Washington, D.C.: U.S. Environmental Protection Agency. EPA 430-R-04-003. 304 pp.

US EPA (2007). "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2005." Washington, D.C.: U.S. Environmental Protection Agency. n/a; public review draft. 453 pp.

US EPA (2008). "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1995 - 2006." Washington, D.C.: U.S. Environmental Protection Agency. EPA 430-R-08-005. 473 pp.